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REVIEW ARTICLE

A comprehensive review on synthesis and application of nanocomposites for adsorption of chromium: status and future prospective

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Abstract

The presence of heavy metals in water bodies can cause major problems for human, plant, and animal life. Excessive amounts or over the prescribed limits of heavy metals in water bodies usually contaminates the water, this type of water is called polluted water and this whole process is known as water pollution. Regular consumption of heavy metal-contaminated water above prescribed limits can cause various diseases and sometimes even lead to death**.** Heavy metals like chromium, arsenic, lead, mercury etc. are more toxic and are easily found in water bodies due to anthropogenic and natural activities. The presence of these heavy metals in water even in tiny concentrations is dangerous to human and animal health. Due to its highly toxic nature, it is paramount to remove these pollutants from water bodies before human use. Adsorption is the best technique to remove these pollutants from wastewater based on cost, efficiency, and feasibility. For the adsorption process, a variety of adsorbent materials have been synthesized by researchers in the past few decades, and yet it remains a challenge for researchers and scientists to synthesize a cost-effective and highly efficient adsorbent. In this prospect, water treatment by adsorption process, nano-composites are emerging materials that show excellent adsorption characteristics due to their outstanding material properties, manageable and low-cost production, and excellent adsorption capacity for chromium adsorption from wastewater. The various nanocomposite adsorbent material prepared by different types of nanoparticles that are supported or embedded on biomass/biochar/graphene/polymer/etc. and used for chromium adsorption have been incorporated. The physio-chemical and structural characteristics of nanocomposites are covered in this review paper. Furthermore, the impact of various adsorption conditions, together with their benefits and drawbacks, on the effectiveness of water treatment are discussed. This thorough review concludes with a summary and some ideas about novel strategies and difficulties in the investigation of advanced and hybrid nanocomposite materials used to remove Cr(VI) from wastewater.

Keywords Water pollution · Chromium · Adsorption · Nanocomposites

Introduction

Pollution is a major environmental issue that occurs when harmful or toxic substances are released into the environment from industrial, geological, and household activities that affect the quality of air, water, and soil. Water pollution is currently a serious and significant environmental problem that affects the quality of water in our life-sustaining rivers, lakes, oceans, and groundwater (Ayoob et al. 2008). Water pollution is caused by the addition of harmful organic and inorganic substances to water, which makes it unfit for consumption by humans and animals and additionally less useful for daily human activities. Water pollution has serious adverse effects on human health and that of animals, as well as a serious impact on our environment. The harmful consequences of water pollution on human health comprise skin irritation, stomach illness, and respiratory problems. It can also cause long-term health issues such as cancer and neurological disorders (Wuana and Okieimen 2011; Kumar et al. 2021). In contrast, animals and aquatic life can experience reduced oxygen levels and chemical accumulation.

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Polluted water can damage plants, leading to disease and reduced growth. The major sources of water pollution include industrial waste, agricultural runoff, sewage, and other human activities such as the extraction of minerals by mining, catalysis industries, oil spills, littering, chemical spills, etc. (Ahmed et al. 2017; Kumar et al. 2018; Afkhami et al. 2010). Agricultural runoff significantly contributes to water pollution, as it contains fertilizers and pesticides that can contaminate the water. Sewage contains bacteria, viruses, and other harmful pathogens that can cause diseases like cholera, typhoid, and dysentery.

Among these sources, industries dealing with heavy metals are of significant concern because of their high persistence in the environment and the ease with which they can enter living organisms, causing long-term exposure and potentially harmful effects. Heavy metals are metallic elements that have high atomic weights and densities. Examples of heavy metals include lead, mercury, cadmium, arsenic, chromium, etc. These metals occur naturally in the Earth's crust, but human activities have greatly contributed to their release into the environment, poisoning all possible sources of water (Agarwal et al. 2016; Ahmad and Mirza 2017). Sources of heavy metals in the environment include industrial activities such as mining and smelting operations, industrial waste disposal, and agricultural runoff. Disposal of industrial wastes containing heavy metals leads to water pollution when the residual is released near nearby water sources, either through direct discharge or groundwater contamination. Fertilizers and pesticides can also be a source of heavy metals in agricultural runoff, which can contaminate water sources. The existence of heavy metals in water bodies is toxic to humans, animals, and aquatic life. Consumption of water containing heavy metals can cause unique health problems, including neurological disorders, cancer, kidney damage, etc. Heavy metals can also accumulate in the bodies of aquatic life, causing reduced growth rates, reproductive problems, and death (Aliabadi Banerjee et al. 2019; Arora and Padua 2010).

Chromium is a heavy metal that is toxic to human health when its concentration in water exceeds the prescribed concentration. Chromium is a corrosion-resistant, steel-gray, solid, and lustrous metallic element primarily found in chromite ore. The two main sources of Cr(VI) pollution are natural and anthropogenic, the latter of which has a high degree of environmental mobility. $K_2Cr_2O_7$ is a common source of chromium (Cr(VI)), which is used in a variety of industries for hot welding steel, electroplating, preserving wood, making alloys and colors, tanning leather, and other purposes (Babel and Kurniawan 2004; Abdel-Sabour 2007; Banerjee et al. 2019) Because of its high melting point, modest thermal expansion, and stable crystalline structure, Cr(VI) is used in many processes, including the fabrication of corrosion-resistant alloys, the solidification of steel alloys, and the pigmentation of glass. Chromium is a metal that exists in several oxidation states, including Cr (0), Cr (III), and Cr (VI). Among these, Cr (III) is an essential nutrient, while Cr(VI) is a toxic and carcinogenic form found mainly in industrial wastes. The toxicity nature of Cr(VI) was due to its fast ability to react with an alive organism, high solubility in water, and oxidation state (Chen et al. 2022; Chu et al. 2020).

Chromium contaminates water sources, yet the sources and routes of contamination are different. Chromium contamination is often related to human activities and industrial processes. The World Health Organization (WHO) has established limits on the concentration of chromium in drinking water to protect public health. The maximum allowable concentration of total chromium in drinking water is 0.05 mg/L. Disease symptoms such as hyperkeratosis, hypertension, cirrhosis, hepatocellular carcinoma, neurological disorders, parenchymal cell damage, muscle weakness, and loss of appetite appear when humans consume even minimal concentrations of chromium (Morrison and Murphy 2010; Dotaniya et al. 2014) whereas chronic consumption of water containing chromium can be fatal and result in various cancers including skin, lung, bladder, and kidney (Kumar et al. 2018; Barnhart 1997). Consequently, regular consumption of contaminated water containing chromium is fatal to humans due to its carcinogenic effects.

Therefore, it is essential to remove chromium from the contaminated water to protect human health and the environment. For this purpose, various technologies have been developed, such as coagulation-flocculation, ion exchange, membrane filtration, advanced oxidation process, adsorption, electrochemical treatment, chemical precipitation, and bioremediation (Basaleh et al. 2019; Beyranvand et al. 2019; Bhanvase et al. 2019; Bhatia and Nath 2020). Figure 1 represents the various technologies for chromium contaminated wastewater.

Table 1 represents the merits and demerits of various wastewater treatment technologies. Among these technologies, adsorption is the best treatment process for the removal of chromium from contaminated water sources. This is because adsorption is a simple, cost-effective, easy to operate, no toxic pollutant release during the process, low by-product formation, and versatile treatment process commonly used to treat a wide variety of pollutants (Bhaumik et al. 2018a; Bhowmik et al. 2019; Biswal et al. 2020).

For the adsorption process, the adsorbent is the material that adsorbs the pollutants from the wastewater.In the last four decades of development, a variety of low-cost adsorbent materials were synthesized and used to adsorb chromium from wastewater.Various types of low-cost adsorbents, such as activated carbon, biochar, red mud, clay, zeolites, fly ash, etc., were synthesized by different synthesis techniques and used as an adsorbent material for adsorption of chromium

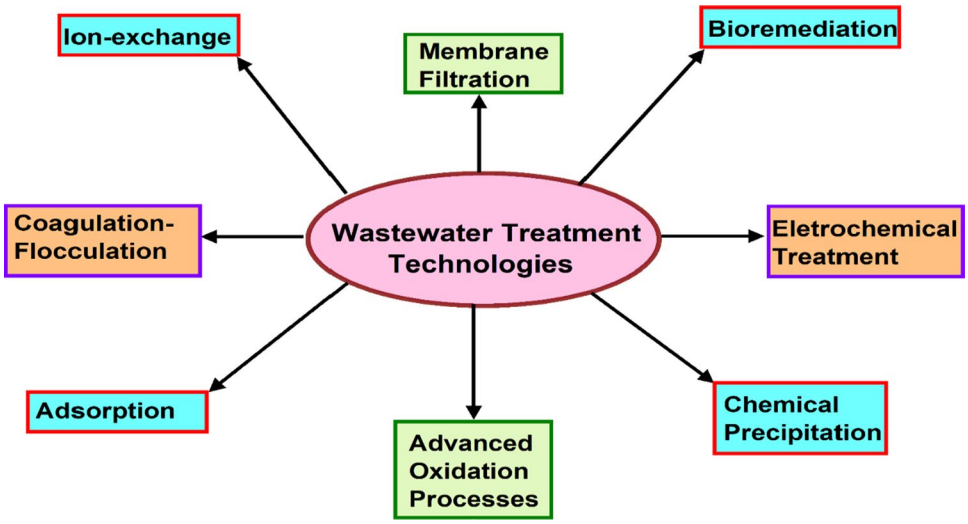


Fig. 1 Various technologies for purification of chromium pollutant from contaminated water

Table 1 Merits and Demerits of wastewater treatment technologies

Sl. no	Technologies	Merits	Demerits
1	Ion exchange	High removal efficiency Fast Rate Metal selection-based process Excellent removal for heavy metals	High capital and maintenance cost Regeneration needed for ion-exchanger Secondary pollutants produce
2	Membrane filtration	Low waste generation Low chemical required Metal selective process Excellent removal for heavy metals	High installation cost High operating and maintenance cost Highly concentrated sludge generation Membrane fouling
3	Chemical precipitation	Low operating cost Simple process	Huge quantity of sludge production High cost of sludge disposal Undesirable when metals concentration is low
4	Coagulation/flocculation	Low operating cost Excellent sludge settling and dewatering characteristics	Large sludge production Chemical depletion Increased volume of sludge produced
5	Electro-chemical	Rapid and effective process Metals selective process Tolerate suspended solids without chemical requirement	High quantity of by-product formation High energy required High initial and capital cost Filtration process for floc separation
6	Adsorption	Wide range of target pollutants Ease of operation Flexibility and simplicity of design High removal rate	Disposal of regenerated adsorbents
7	Advance oxidation process	Rapid rate Low area/footprint for required Mineralization of organic Used for all organic contamination treatment Some heavy metals are also treated No sludge production	Relatively high capital High operating /maintenance costs Complex chemistry during treatment Removal of residual peroxide
8	Bio-remediation	Low operation cost Low side/area required The natural ability of the microorganism to extract chemical Cost-effective technique Less energy required	Bioremediation is a slow process does not use for all types of contaminants Not suitable for inorganic compound Chemical reaction performance evaluations are complex Sometimes toxic by-product formation

from wastewater (Chang et al. 2016; Chawla et al. 2017; Chen et al. 2019). Figure 2 illustrates the different types of adsorbent materials used in the treatment of chromium-contaminated wastewater. An adsorbent that can meet the needs of both pilot and commercial scales is still needed to be discovered. Good adsorption capacity, an easy synthesis process, low cost, excellent selectivity, fast kinetics, and a rapid desorption rate are the characteristics of the promising adsorbent (Kumar et al. 2020). Carbonaceous materials are not always the most promising adsorbents for the adsorption chromium due to some reasons, such as:

- *Selectivity*: Very low selectivity for arsenic and chromium because they adsorb other compounds present in wastewater, reducing the effectiveness of targeting pollutants.
- *Regeneration and reuse issues*: Arsenic and chromium-loaded materials regeneration and reusability are very difficult and create secondary pollutants.
- *Cost estimation*: The cost of synthesizing carbonaceous materials for large-scale wastewater treatment is very high.

The use of nanotechnology for the treatment of chromium offers several advantages over traditional adsorbents, making it a promising option for effective and efficient water treatment. Nanomaterials have a high surface area, fast kinetics, reasonable regeneration rate, excellent selectivity, and good adsorption capacity due to surface charge, surface chemistry, and pore size distribution (Chowdhury et al. 2020; Gisi et al. 2016).The use of nanoparticles (NPs) for the treatment of wastewater contaminated with chromium offers several advantages over traditional adsorbents, making them a promising option for effective and efficient water treatment. However, it is important to consider the potential toxicity and environmental impact of nanoparticles in wastewater treatment (Lima et al. 2007; Dil et al. 2018).

This review article is written to explain and explore the outcomes of the role of NCs in the treatment of chromium-contaminated wastewater. There are few lately published research articles on NCs; however, most of these papers focus mainly on the synthesis and adsorption of chromium performance aspects (Amari et al. 2021) This assignment is unique in itself, as it includes a detailed discussion of the synthetic methods, a comparative study with other NCs as adsorbents, and adsorption reaction mechanisms involving NCs for the removal of chromium from wastewater. In addition, some of the most recently published research articles related to the adsorption of chromium by NCs for wastewater treatment are also covered and discussed in order to rev the advancement of future work in this specialization.

Nanocomposites

Nanocomposite materials are a class of materials that are composed of at least two components: a matrix material and nanoparticles. The nanoparticles are typically inorganic and have at least one dimension in the nanoscale range, usually between 1–100 nm. The matrix material can be organic or inorganic, and it can be a polymer, metal, or ceramic. The addition of nanoparticles can significantly enhance the mechanical, electrical, thermal, and optical properties of the matrix material, making it a versatile material with a wide

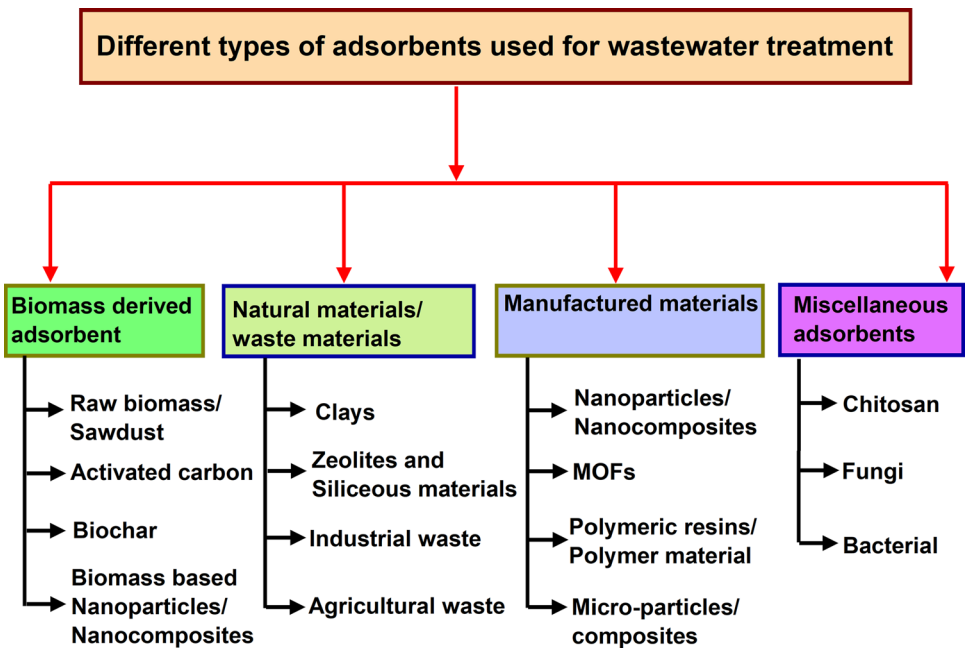


Fig. 2 Classification of different types of adsorbents that used for wastewater treatment

range of applications. The high surface area-to-volume ratio of nanoparticles provides enhanced surface reactivity, which can lead to improved mechanical, thermal, and electrical properties (Dinh et al. 2020a; Dokmaji et al. 2020; Dotto et al. 2016). The nanoscale dimensions of the nanoparticles also allow for the creation of novel hybrid materials with unique functionalities (Elfeky et al. 2017).

Nanocomposites can be synthesized using a variety of methods, including solution blending, melt blending, in-situ polymerization, and layer-by-layer assembly. Solution blending involves dissolving both the matrix material and nanoparticles in a solvent and then mixing them to create a homogenous solution (Etemadinia et al. 2019; Ghosal and Gupta 2017). Melt blending involves mixing the matrix material and nanoparticles in the molten state, followed by cooling and solidification (Guo and Bulin 2021). In-situ polymerization involves synthesizing the matrix material in the presence of the nanoparticles (Halder and Islam 2015; Han et al. 2008). Layer-by-layer assembly involves alternating layers of the matrix material and nanoparticles to create a multi-layered structure.Nanocomposite materials have shown great promise in a variety of applications, including electronics, energy storage, catalysis, and biomedical devices (He et al. 2019; Heidarizad and Şengör 2016; Hossain et al. 2018). For example, the incorporation of nanoparticles into electronic devices can improve their performance and reduce their size. The use of nanocomposites in energy storage devices such as batteries and capacitors can increase their energy density and improve their cycling stability.

Types and application of nanocomposites

The type of matrix material and the type of reinforcement material can be used to categorize nanocomposites. The matrix material can be polymer-based, ceramic-based, metal-based, or hybrid. The reinforcement material can be in the form of nanoparticles, nanofibers, or nanotubes.There are many types of nanocomposites which can be classified on the basis of mechanical, chemical and their application, such as:

1. *Polymer-based nanocomposites*: These are materials in which a polymer matrix is reinforced with nanoparticles or nanofibers to enhance its mechanical, electrical, or thermal properties (Huang et al. 2017). Examples include polyethylene nanocomposites, polystyrene nanocomposites, and polyamide nanocomposites.
2. *Ceramic-based nanocomposites*: These are materials in which a ceramic matrix is reinforced with nanoparticles or nanofibers to improve its mechanical, electrical, or thermal properties (Ibrahim 2019). Examples include aluminum oxide nanocomposites, silicon carbide nanocomposites, and titanium dioxide nanocomposites.
3. *Metal-based nanocomposites*: These are composed of a metal matrix, such as aluminum, copper, or titanium, reinforced with nanoparticles or nanotubes (Saharan et al. 2023). Metal-based nanocomposites are used in various applications, such as aerospace structures, electronic devices, and energy storage, due to their high strength, conductivity, and corrosion resistance.
4. *Carbon-based nanocomposites*: Nanocomposites are composite materials that consist of carbon-based matrices, such as carbon nanotubes (CNTs), graphene oxide (GO), and carbon fibers such as biomass, activated carbon and biochar, reinforced with various nanoparticles, such as metal, metal oxides, or clay particles. These nanocomposites possess unique mechanical, electrical, and thermal properties that make them attractive for various applications, such as energy storage, environmental remediation, and biomedical engineering (Jumadi et al. 2019).
5. *Magnetic-based nanocomposites*: Magnetic-based nanocomposites are composite materials that contain magnetic nanoparticles, such as iron oxide such as Fe_3O_4, Fe_2O_3, FeOOH, nZVI, dispersed within a non-magnetic matrix, such as polymers, silica, or carbon-based materials such as graphene, graphene oxide, biomass, activated carbon, biochar, etc. (Kabiri et al. 2011; Kamal et al. 2020). The presence of magnetic nanoparticles imparts magnetic properties to the nanocomposite, making them attractive for various applications, such as wastewater treatment, magnetic separation, drug delivery, and sensing.
6. *Bio-nanocomposites*: Bio-nanocomposites are composite materials that are composed of both biological and nanoscale components. The biological component can be a polymer, such as chitosan, while the nanoscale component can be nanoparticles, such as silver or gold, or nanofibers, such as cellulose or silk (Kataria and Garg 2017, 2019; Katata-Seru et al. 2020). The combination of biological and nanoscale components imparts unique properties to the composite material, making them suitable for various applications, such as biomedical engineering, food packaging, and water treatment.

All above described NCs have unique properties due to their small particle size, large surface area, tremendous functionality, etc., making them suitable for various applications in different fields. Figure 3 shows the various applications of NCs in several fields.

Nanocomposite for wastewater treatment

Nanocomposites (NCs) offer several advantages, including stability, selectivity, larger surface area, reusability, and flexibility, compared to nanoparticles in the treatment of

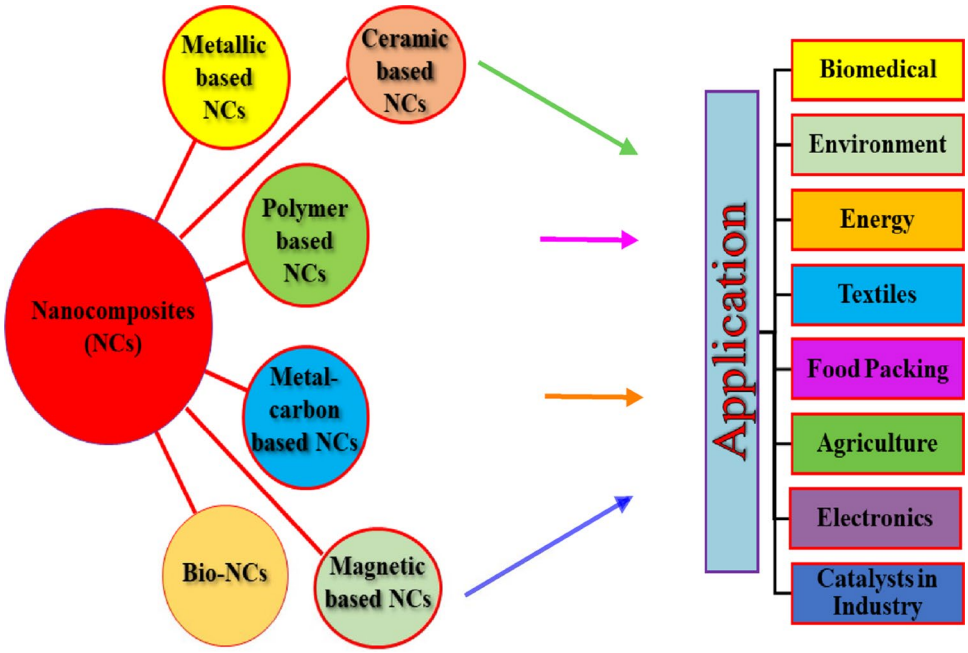


Fig. 3 Applications of various types of NCs in different fields

wastewater (Khalili et al. 2018). In addition, the filtration problem caused by NPs in water treatment can also be solved to a large extent by NCs. These advantages make nanocomposites a promising option for addressing water pollution and improving water quality. Due to all these factors, many studies have been done to synthesize nanocomposites with the vision of amalgamating the advantageous qualities of nanoparticles and other matrix materials. At the same time, efforts were made to erase their personal boundaries to a great extent. In disparity to nanoparticles, biochar, activated carbon, clay, polymers, etc., NCs are reported to exhibit several beneficial properties, such as high mechanical strength, high surface area, tremendous functionality, good stability, low production cost, and high pollutant adsorption capacity (Khalith et al. 2021a; Khan and Malik 2018).

Kumar et al. (2014) produced NCs with a hybrid structure of manganese ferrite magnetic nanoparticles doped on single-layer graphene oxide and used NCs as an adsorbent for the removal of Pb (II), As (III), and As (V) from polluted water samples (Kumar et al. 2014). The maximum adsorption capacity was 673 mg/g, 146 mg/g, and 207 mg/g for Pb(II), As(III), and As(V), respectively. Because of its large adsorption capacity and simplicity of magnetic separation, it looked promising material for the co-removal of numerous heavy metals or metalloids from aquatic environments. Konicki et al. (2012) synthesized an effective M-MWCNT–Fe_3C nanocomposite for the adsorption of red 23 dye from wastewater with a maximum adsorption capacity of 85.5 mg/g (Khoshsang et al. 2018).The noticeable point is that after adsorption, the spent adsorbent was easily separated from the solution by using an external magnetic field.Biochar/MgO nanocomposites fabricated by Hua et al. (2012) showed an adsorption capacity of 835 mg/g for phosphate, which was too high. The high phosphate adsorption capacity of NCs was due to multiple mechanisms, including ion exchange, co-precipitation, surface complexation, and cation interaction (Kittappa et al. 2015).In the anther study, according to Lu et al. (2015), poly(1-vinylimidazole)-grafted Fe_3O_4@SiO_2 nanocomposite showed a 346 mg/g adsorption capacity for Hg(II) at pH 7, and the exhausted adsorbent may be produced in under 10 min by using a 0.50 M HCl solution (Kloster et al. 2019). These results confirmed that NCs have excellent adsorbent materials for wastewater treatment.

Most NCs are relatively inexpensive and can be reused after several regeneration cycles using the chosen eluent. In addition, magnetic-based nanocomposites have attracted great attention among other nanocomposites due to their excellent adsorption capacity for heavy metals such as arsenic, chromium, lead, etc. Iron-based nanocomposites offer several advantages for the adsorption of arsenic and chromium from water, including high adsorption capacity, selectivity, cost-effectiveness, regenerability, environmental compatibility, and scalability. These advantages make iron-based nanocomposites a promising material for use in chromium-contaminated water treatment.

Iron-based nanocomposite applications are diverse, but in water treatment, iron-based nanocomposites are mainly used or are being used. The iron nanoparticles in iron-based nanocomposites are predominantly nanoscale zero-valent iron (nZVI), FeOOH, Fe_3O_4, α-Fe_2O_3 and ɣ-Fe_2O_3, of which Fe_3O_4, α-$Fe_2O_3$and ɣ-Fe_2O_3 are known as magnetite, hematite and maghemite, respectively (Laabd et al. 2016;

Lei et al. 2017, 2016a).Iron-based nanocomposites exhibit superparamagnetic behavior. Therefore, magnetic properties can only be observed in an external magnetic field. Due to their magnetic properties, iron-based nanocomposites can be shown to be a more reliable material for water treatment because the material can be easily separated after water treatment, which increases the possibility of its reuse (Lei et al. 2016b; Li et al. 2020).Furthermore, iron is abundant on the Earth's surface, less expensive, and has less toxicity to our ecosystem than other toxic elements. Its magnetic nature has led to the synthesis of iron-based nanocomposites, which have had a wide impact on environmental remediation (Li et al. 2017a).The effectiveness of iron-based nanocomposite materials in removing inorganic and organic contaminants from contaminated water has been demonstrated.

Adsorption of Cr(VI) by NCs as adsorbents

Khalith et al. (2021) synthesized magnetite carbon nanocomposite via the green method using two agro wastes such as sugarcane bagasse and orange peels (Khalith et al. 2021b). The orange peel extract (OPE) was used as capping and reducing agents, and sugarcane bagasse was used for the synthesis of highly porous carbon (HPC) by treatment of H_3PO_4 acid at 450 °C for 3 h. The Fe^{2+} and Fe^{3+} precursors were added to the OPE extract solution in a 1:2 ratio to synthesize magnetite carbon nanocomposites. Then HPC was slowly added to the metal contain OPE extract solution. After that, the solution was stirred continuously for 3 h and finally the obtained product was calcined at 500 °C for 5 h. The synthesized NCs were characterized by XRD(X-ray diffraction), FT-IR(Fourier transform infrared spectroscopy), UV–Visible (Ultraviolet–Visible Spectroscopy), TEM (transmission electron microscopy), and SEM (Scanning electron microscope) techniques. The FT-IR spectra of NCs confirmed that NCs contained various functional groups such as C–O–C, –C–OH, $=NH_2$, Fe–O, etc., responsible for the Cr(VI) adsorption. The XRD pattern of the synthesis showed various peaks due to the presence of iron and carbon content, and due to the presence of iron, NCs showed a high crystalline structure. SEM and TEM investigated the morphology of magnetite carbon nanocomposite, and results confirmed that FeO NPs were rod-shaped, and deposited on irregular sheets of carbon. The adsorption experiments were performed for Cr(VI) removal from wastewater to examine the various affecting parameters such as initial pH, contact time, adsorbent dose, initial Cr(VI) concentration, temperature, and agitation speed. The maximum removal (~ 99%) of Cr(VI) was found at pH 5.5 for 30 mg/L concentration of Cr(VI) within 4 h at 35 °C. The authors also noticed an interesting point that upon increasing the adsorption dose, the removal percentage of Cr(VI) decreased due to the accumulation of particles. The kinetic and equilibrium data were fitted with various kinetic and isotherm models. According to results, the pseudo-second-order kinetic model and Langmuir isotherm model were best described the adsorption phenomena.

Furthermore, chitosan-MnO_2 nanocomposite was synthesized by Dinh et al. (2020) and utilized synthesized NCs as an adsorbent for Cr(VI) removal from aqueous solution (Dinh et al. 2020b). The chitosan-MnO_2 NCs were synthesized by a chemical method using potassium permanganate, ethanol, and chitosan regents. The authors performed detailed characterization to examine the physio-chemical properties of synthesized NCs via SEM, TEM, TGA, FT-IR, point of zero charge, and XRD techniques. The SEM analysis gives the information related to the morphology of NCs, and results found that MnO_2 NPs coated with chitosan whose surface was porous with the rugged surface. The XRD pattern of NCs showed four strong peaks that were assigned to α-MnO_2. The FT-IR analysis confirmed the presence of various functional groups with metal–oxygen bonding. The point of zero charge of NCs was found 7.2 by using of solid addition method. All the adsorption factors, which affect the adsorption efficiency of NCs, such as initial pH, contact time, initial Cr(VI) concentration, presences of other ions and NCs dosage, were also analyzed in batch mode. The effect of pH was investigated from pH 2 to 11, and it was found that maximum removal occurred at pH 2 due to electrostatic attraction between positively charged surface of NCs and negatively charged chromium species that formed at lower pH. The effect of NCs dose and initial Cr(VI) concentration showed opposite trends due to an increase in the availability of active sites and unavailability of active sites in NCs, respectively. The presence of KCl in the Cr(VI) solution reduced the percentage removal of Cr(VI) when present in higher concentrations due to competition between the same charge densities. The Langmuir, Freundlich, Sips, Temkin, and Dubinin-Radushkevich isotherm models were fitted equilibrium data. The authors found Sips model combination of Langmuir and Freundlich isotherm was best suited to the experimental data, which indicated both monolayer and multilayer adsorptions occurred on the surface of NCs. The maximum Langmuir monolayer adsorption capacity of NCs was 61.56 mg/g at pH of 2 within 120 min contact time. The pseudo-second-order model was well described the chemisorption phenomena based on high correlation coefficient (R^2) and low root mean square error (RMSE) and mathematically error functions (χ^2) values compared to pseudo-second-order and intra particle diffusion models. The thermodynamic study concluded that Cr(VI) adsorption onto NCs was spontaneous, favorable, and endothermic. The authors have described the possible adsorption mechanism for adsorption of Cr(VI) on chitosan-MnO_2 NCs based

on electrostatic attraction between the surface of NCs and Cr(VI) species.

In another study, a Fe_2O_3-Ag nanocomposite was synthesized by Biswal et al. (2020) via a green method in which *Psidium guajava* leaf extract solution was used as capping and reducing agents (Biswal et al. 2020). In the synthesis process, both iron and silver precursor solution was prepared separately into water solution in 0.1 M concentration and mixed both solutions with the constant stirred condition. After proper mixing, the leaf extract solution was added drop by drop to this solution until the precipitate was formed. The synthesized Fe_2O_3–Ag NCs were characterized by various techniques to examine the specific physiochemical and structural properties. The crystallinity phases of NCs were examined by XRD analysis, and results confirmed that face-centered cubic phase of Ag nanoparticles with a rhombohedral crystal structure of α-Fe_2O_3 NPs found in NCs. The BET surface area showed high values (112.72 m^2/g) compared to other NPs. The FT-IR analysis confirmed the presence of various functional groups other than metal-oxide due to leaf extract containing various phenolic, alcoholic, and proteins compounds, which are responsible for reducing silver and iron. FE-SEM techniques examined the morphology of synthesized NCs, and authors reported that NCs highly aggregated and formed irregular shapes with 50–90 nm size. The green method synthesized NCs was used to remove hazardous oxyanion hexavalent chromium from an aqueous solution in batch mode experiments. The maximum removal of Cr(VI) by NCs was reported at pH 4 and decreased on increasing pH. The equilibrium condition was found within 120 min. The removal percentage of Cr(VI) increased with increasing NCs dose up to 0.5 g/L and approximately constant reported when dose increased from 0.5 g/L due to unavailability of pollutants molecules in solution. The pseudo-second-order and Langmuir isotherm model were best fitted experimental data, and the maximum monolayer adsorption capacity of NCs was 112.72 mg/g reported at pH 4. The effect of coexisting anions on removal percentage was also investigated by authors and found that SO_4^{2-} and PO_4^{3-} highly affected the adsorption rate compared to Cl^-, CO_3^{2-} and NO_3^- anions. Thermodynamic studies were also performed within 20 to 50 °C temperature range, and the results confirmed that the process was spontaneous and endothermic.

Katata-Seru et al. (2020) investigated Cr(VI) removal by utilizing of a polypyrrole/nanoscale zero-valent iron (Ppy/Fe^0 NCs) nanocomposite as an adsorbent (Katata-Seru et al. 2020). The NCs were produced by two methods in which nanoscale zero-valent iron was synthesized by the green method and polypyrrole/nanoscale zero-valent iron (Ppy/Fe^0) NCs produced by the in-situ oxidative polymerization method. The structure and functional groups related properties of Ppy/Fe^0 NC were investigated using various analytical techniques as earlier discussed in the literature. The XRD pattern of NCs contained three broad peaks at $2\theta = 10°$, 25°, and 44.8° assigned to presence of organic compound (polyphenols and flavanoids), polymer and crystalline Fe^0 NPs, respectively, and average particles size of NCs was 4.56 nm. The FE-SEM morphology analysis confirmed that NPs were in spherical shape with highly agglomerated due to in-situ polymerization. The FT-IR and EDX analysis confirmed that carbon, oxygen, and iron metals were the main elements in NCs. Carbon and oxygen formed the influential functional groups that took place in the adsorption process. The surface area of Ppy/Fe^0 NCs was reported 45.13 m^2/g which was higher than individual Fe^0 NPs and polypyrrole. An increase in the surface area was seen by the authors due to the reduction in the larger particles size, which also led to an increase in the adsorption capacity of the synthesized NCs. To find the optimized conditions for adsorption, various factors which affected the adsorption were also investigated. The adsorption of Cr(VI) is highly dependent on the pH of the solution; therefore, the authors investigated the effect of pH on Cr(VI) adsorption from pH 2–12. When the initial pH of the solution was increased from 1 to 12, the adsorption decreased from 73 to 32% and maximum removal occurred at pH 2. The adsorption equilibrium was reached within 75 min for 25 mg/L concentration, and the equilibrium time was also changed with the increasing initial concentration of Cr(VI). The authors concluded from kinetic modeling parameters that pseudo-second order best described the Cr(VI) adsorption compared to the pseudo-first-order model. Based on the correlation coefficient (R^2) values, the Langmuir model was more preferred for the adsorption than the Freundlich model and the maximum monolayer adsorption capacity of NCs was 202.02 mg/g. The effect of coexisting cations and anions were also reported by authors from 0 to 200 mg/L and results revealed that both positive and negative charged NCs was much not affected by NCs from 0 to 200 mg/L concentration of cations/anions.

Some other novel NCs as adsorbents for adsorption of Cr(VI) from aqueous solution with synthesis method, characterization tool, and various parameters such as initial pH, equilibration time, initial concentration, temperature are also summarized in Table 2 also includes information related to the synthesis method for NCs, surface area of NCs, optimized conditions for adsorption and maximum adsorption capacity of NCs.

Wastewater treatment is becoming more and more important due to the world's rising urbanization and the need for clean water for sustainable development (Mpongwana and Rathilal 2022). The inability of many developing nations to invest in the required infrastructure, however, makes it unlikely that they will be able to reach sustainable development. Although high implementation costs are still a problem, nanotechnology is thought to be a promising technology

Table 2 Adsorption of Cr(VI) by NCs/NPs as adsorbents

S. no.	Author	Adsorbent (NCs)	Synthesis method	Surface area (m^2/g)	Optimized performance parameter	Q_{max} (mg/g)	References
1	Long et al. (2021)	Calcined Mg/Al-layered double hydroxides/polyaniline composites	Oxidative polymerization	49.24	pH: 2–10; contact time: 24 min; Cr(VI) concentration: 20–120 mg/L; NCs dose: 0.1 g/L; Temperature: 20–40 °C; effect of coexisting anions (Cl^-, $H_2PO_4^-$, NO_3^- and SO_4^{2-}): 5–20 mmol/L	409.77 mg/g at pH 2 and 20 °C	Li et al. (2021)
2	Kumar et al. (2023)	CTAB modified Multiwall carbon nanotubes (MWCNTs) nanoparticles	Chemical mixing	164.8	pH: 2–5; contact time: 120 min; Cr(VI) concentration: 50–210 mg/L; NCs dose: 1–8 g/L; Temperature: 25–35 °C	66.2 mg/g	Kumar et al. (2023)
3	Li et al. (2020)	CTAB-surface-functionalized magnetic MOF@MOF (Fe_3O_4@UiO-66@UiO-67/CTAB) composite	Solvothermal method	115.94	pH: 1–11; contact time: 1400 min; Cr(VI) concentration: 5–500 mg/L; NCs dose: 20 mg; Temperature: 25–45 °C; effect of coexisting ions (Na^+, Ca^+, Mg^{2+}, Cl^-, PO_4^{3-}, NO_3^- and SO_4^{2-}): NA	932.1 mg/g	Li et al. (2020)
4	Singh and Rachna, (2020)	Copper ferrite-Polyaniline nanocomposite	Coprecipitation followed by calcination at 500 °C	–	pH: 2–10; contact time: 40 min; Cr(VI) concentration: 20–60 mg/L; NCs dose: 12.5–50 g/L; Temperature: 30–70 °C	250 mg/g	Singh and Rachna (2020)
5	Iqbal et al. (2021)	ZnO with cotton stalks biochar nanocomposite	Precipitation method	–	pH: 2–8; contact time: 180 min; Cr(VI) concentration: 25–200 mg/L; NCs dose: 1–4 g/L; Temperature: 25 °C	107.53 mg/g	Iqbal et al. (2021)
6	Yu and Fu (2020)	Core–shell Fe_3O_4@Ce-Zr oxide composites	Coprecipitation method	133.3	pH: 3, 5, 7, 9; contact time: 180 min; Cr(VI) concentration: 20–150 mg/L; NCs dose: 0.5–1.25 g/L; Temperature: 25 °C; effect of coexisting ions (Cu^+, Ni^+, Cl^-, PO_4^{3-}, SiO^{4-} and SO_4^{2-}): 0–50 mg/L	66.7 mg/g	Yu and Fu (2020)
7	Sharma et al. (2019)	ZnOtetrapods and activated carbon composite	Flame transport synthesis (FTS) approach	642.70	pH: 2–8; contact time: 420 min; Cr(VI) concentration: 0–240 mg/L; NCs dose: 1–5 g/L; Temperature: Room temperature	–	Sharma et al. (2019)

Table 2 (continued)

S. no.	Author	Adsorbent (NCs)	Synthesis method	Surface area (m^2/g)	Optimized performance parameter	Q_{max} (mg/g)	References
8	Zhang et al. (2019)	Biochar supported CMC stabilized nano zero-valent iron (biochar-CMC-nZVI) Composite	Chemical method with reduction	6.2–11.6	pH: 3–9; contact time: 0–1440 min; Cr(VI) concentration: 5–200 mg/L; NCs dose: 0.75–1.25 g/L; Temperature: 25 ± 2 °C	112.5 mg/g	Zhang et al. (2019)
9	Bhaumik et al. (2018)	Polyaniline@ $Ni(OH)_2$ nanocomposites	Chemical method and polymerization	26.85	pH: 3–11; contact time: 180 min; Cr(VI) concentration: 100–500 mg/L; NCs dose: 0.05–0.5 g/L; Temperature: 25–45 °C; rpm speed: 50–200; effect of coexisting ions (Zn^+, Co^+, Cu^{2+}, NO_3^- and SO_4^{2-}): 100–200 mg/L	625 mg/g at 25 °C	Bhaumik et al. (2018b)
10	Zhang et al. (2018)	Reduced graphene oxide/NiO(rGO/NiO) nanocomposites	Facile chemical method	–	pH: 2–11; contact time: 2000 min; Cr(VI) concentration: 20–120 mg/L; NCs dose: 0.33 g/L; Temperature: 10–50 °C	198 mg/g at pH 4	Zhang et al. (2018)
11	Elfeky et al. (2017)	CTAB modified magnetic (Fe_3O_4) nanoparticles	Coprecipitation and chemical mixing	–	pH: 4–9; contact time: 720 min; Cr(VI) concentration: 100 mg/L; NCs dose: 4–12 g/L; Temperature: 25 °C; effect of coexisting ions: PO_4^{3-}, NO_3^- and SO_4^{2-})	18.5 mg/g	Elfeky et al. (2017)
12	Fu et al. (2017)	$MnFe_2O_4$@SiO_2-CTAB Composites	Hydrothermal method followed by modification	53.4	pH: 3–9; contact time: 180 min; Cr(VI) concentration: 0–240 mg/L; NCs dose: 2.8 g/L; Temperature: 25 °C	25.044 mg/g	Li et al. (2017b)
13	Shekari et al. (2017)	Nickel ferrite /titanium oxide magnetic ($FeNi_3$/TiO_2) nanocomposite	Chemical method	–	pH: 2–10; contact time: 40 min; Cr(VI) concentration: 0.04–10 mg/L; NCs dose: 0.2–0.9 g/L; Temperature: 30–70 °C	76.33 mg/g	Shekari et al. (2017)
14	Wang et al. (2017)	Multifunctional graphene oxide-based magnetic nanocomposite	Oxidation–reduction reaction	–	pH: 2–7; contact time: 1500 min; Cr(VI) concentration: 10–100 mg/L; NCs dose: 1–0.14 g/L; Temperature: 30–60 °C	–	Wang et al. (2017)

for environmentally friendly wastewater treatment (Karaouzas et al. 2021). The economic viability of utilizing nanoparticles for coagulation and adsorption in the treatment of textile wastewater—such as Fe/Cu nanoparticles has been investigated in a few research. Potential cost savings come from reusing nanoparticles and using green production techniques (Gu et al. 2020). The results demonstrate that adsorption is still expensive even in the presence of green nanoparticles. Production costs for nanoparticles can be somewhat significant and vary depending on the nation. Costs can be decreased by combining nanotechnology with conventional techniques (Dimapilis et al. 2018). More affordable options have been investigated, such as using rice husk for Cu(II) adsorption or agricultural waste as an absorbent for heavy metals (Qasem et al. 2021). When evaluating these expenses, the state of the local economy must be taken into account (Simeonidis et al. 2019).

Future prospects and conclusions

The purpose of this brief review article is to outline several methods of nanocomposite synthesis for the adsorption of Cr(VI) from wastewater. Additionally, the specific properties of the nanocomposites, such as BET surface area, functionality, adsorption capacity for pollutants, and optimum conditions for the adsorption process, were discussed. Although a variety of water treatment adsorbent materials for adsorption processes are widely available, new nanotechnologies using nanocomposites are much cheaper, cost-effective, and highly efficient materials for water treatment. The application of nanocomposites as adsorbent material for the adsorption process is a new technology being pursued in the treatment of Cr(VI) polluted wastewater. The nanocomposites exhibit high BET surface area, unique surface structure, enhanced functionality, and active sites due to the presence of 2-phases or more phases. Following this review, it was found that pH 2 was the optimal temperature for Cr (VI) adsorption. However, most of the research articles presented significant stability for NCs, which was substantially better than for nanoparticles. This suggests that the nano-composite will be a useful material for Cr (VI) adsorption. The nanocomposite materials are not only discussed for applications in water treatment, scientists also try to discourse how they could be useful in other techniques of the energy field, antibacterial materials, photocatalysts, sensors, and anti-biofouling compounds.

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Declarations

Conflict of interest The authors declare no competing financial interest.

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